Report of the MIT Taskforce on

INNOVATION and PRODUCTION

2013

A Preview of the MIT Production in the Innovation Economy Report

February 22, 2013

A Preview of the MIT Taskforce on Innovation and Production Reports

Two books to be published in FALL 2013

MAKING IN AMERICA

From Innovation to Market

Suzanne Berger with
the MIT Task Force on Production in the Innovation Economy

and

PRODUCTION IN THE INNOVATION ECONOMY

Editors: Richard M. Locke and Rachel Wellhausen

MIT Press, 2013

The research of the MIT Production in the Innovation Economy project was supported by grants from Alfred P. Sloan Foundation, Carnegie Corporation of New York, Russell Sage Foundation, and The Ewing Marion Kauffman Foundation, and generous gifts from three MIT alumni, Mark Gorenberg, Diane Greene, Ray Stata, and from the Lockheed Martin Corporation. We are grateful also for the research assistance provided by the Center for Survey Research at the University of Massachusetts. Above all, we wish to thank the hundreds of people we interviewed in the course of the research who took hours from busy workdays to talk with us. However skeptical they may have been about academic research, they were unfailingly generous with time and insights. We have received permission to cite some of them by name; others wished to remain anonymous. We owe them all a great debt.

Neither the donors nor the interviewees bear any responsibility for the findings reported by the MIT Production in the Innovation Economy group or for its recommendations.

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Introduction

Over the past decade, as millions of jobs disappeared in a flood of Asian imports and a severe financial and economic crisis, pessimism about the future of production in the United States swept across the country. People started to question whether U.S. manufacturing could ever compete with Asian low-wage production. The trade deficit in advanced technology products deepened—equal to 17 percent of the total U.S. trade deficit by 2011—and it seemed that even high-tech sectors of industry were doing better overseas than here. As in past times of trouble, some blamed foreign governments for damaging U.S. manufacturing by subsidizing their own companies and protecting their national currencies. But even the critics of foreign governments knew there was something wrong at home.

Everyone agreed that the U.S. needed a higher rate of good job creation, but no one seemed to know where jobs could come from. Could manufacturing jobs come back? The brightest corporate superstars, like Apple, were locating production abroad and still reaping the lion's share of profits within the U.S. Was this going to be the American model for the future? In emerging technology sectors, like batteries, solar, and wind, even when the startups were created in the U.S. out of U.S. innovations, commercialization of the technology was taking place abroad. What could Americans do to leverage their strengths in new science and technology to rebuild a dynamic economy? Would production capabilities at home be needed to capture the flow of benefits from invention and entrepreneurship? Which capabilities? And how could they be created and sustained?

The anxieties of the public connected with many of our own deep concerns at MIT about where the American economy is heading. MIT's dual mission is educating students and creating new knowledge. What motivates the people who do this is desire to contribute to understanding the great mysteries of nature and to solving the great problems of the world: disease, conflict and violence, poverty, energy, climate change. Even for those investigating the puzzles of the natural world, the question of how their knowledge might be used is never far away. At a time of economic crisis, when it is hard to figure out who will benefit and how from our research, or what our students will have as opportunities in career and life, the alarm bells sound loud in our halls. In one such previous moment, at the end of the 1980s, MIT's President Paul Gray had asked faculty members from across the specialized disciplines of the Institute to work together to analyze the causes of slow productivity growth and industrial stagnation in the United States and to propose new approaches for private industry, government, and universities. The book the group wrote was *Made in America*, and it became a landmark in public debates about the U.S. economy.[1]

1 Michael L. Dertouzos et al., *Made in America: Regaining the Productive Edge* (Cambridge MA: MIT Press, 1989).

With that legacy in mind, in 2010 MIT President Susan Hockfield launched the MIT Production in the Innovation Economy (PIE) research group. Twenty faculty members and a dozen students joined. The objective was to analyze how innovation flows from ideas through production into the economy. The point of departure was recognizing that innovation is critical for economic growth and for a vibrant and productive society. Our question was: what kinds of production do we need—and where do they need to be located—to sustain an innovative economy? In our work we have tended to use the terms "manufacturing" and "production" interchangeably. It's true, as Professor Richard Freeman, a Harvard economist, has put it, that a person knows it's manufactured when he drops it on his foot. But in most of the firms in which we carried out our research the traditional line between "manufacturing" and "services" has become so blurred that it no longer serves to distinguish separable and distinct activities or end products. Whether in a giant like Apple or in a small Ohio company that makes half-sleeves to repair pipelines and sends its technicians along with the product to stand on the oil platforms and shout down instructions to the divers, the activities that create most value, that is, the ones that are most difficult for others to replicate, are bundles of an object you could drop on your foot and of services. We focused on those bundles, and we structured our inquiry to locate opportunities and dangers for American prosperity in the changes that have taken place over the past thirty years in the linkages between an innovation and the broad range of production processes that bring it to market.

There are many serious reasons to worry about the fate of manufacturing in the United States. And after years of relative neglect as a subject for academic inquiry, there has been an outpouring over the past four years of commentary and research on these issues. Virtually every week brings a new report diagnosing the state of manufacturing and emphasizing different aspects of its critical significance for the economy.[2] One of the key danger points identified in these reports is the declining weight of the U.S. in the global economy. Even though the U.S. share of world manufactured output has held fairly steady over the past decade, economists have pointed out that this reflects good results in only a few industrial sectors. And even in those sectors, what appear to be productivity gains may be the result of underestimating the value of imported components. A close look at the composition of a worsening trade deficit shows that even in high-tech sectors the U.S. has a deteriorating picture. While the output of U.S. high tech manufacturing is still the largest in the world and accounted for $390 billion of global value added in high-tech manufacturing in 2010, U.S. share of this world market has been declining, from 34 percent in 1998 to 28 percent in 2010, as other countries made big strides ahead into this market segment.[3] Jobs are another huge

2 Among the early and most systematic attempts to lay out the range of dangers for the United States resulting from weaknesses in manufacturing was Gregory Tassey, "Rationales and Mechanisms for Revitalizing U.S. Manufacturing R&D Strategies," *Journal of Technology Transfer* 35, no. 3 (2010).

3 National Science Board, "Science and Engineering Indicators 2012," (Arlington VA: National Science Foundation 2012). [6- 21, 22].

concern. The great spike in unemployment over the past five years was disproportionately due to loss of manufacturing jobs. And as the economy revived, such jobs were very slow to return. In fact it is clear that many of them never will. Over the long postwar years of prosperity, manufacturing jobs had been especially valuable to workers and valuable for middle-class opportunity because they paid higher wages and had better benefits than other jobs available to people with educational qualifications of high school or less. New manufacturing jobs now often come with lower wages and fewer benefits attached. National security is also linked to the health of manufacturing through the procurement of new weapons and the maintenance and replacement parts for the many generations of equipment still in service. The wave of disappearance of many small- and medium-sized suppliers creates worrisome and still relatively unknown degrees of dependence on foreign suppliers for U.S. military contractors. Across the entire industrial landscape there are now gaping holes and missing pieces. It's not just that factories stand empty and crumbling; it's that critical strengths and capabilities have disappeared that once served to bring new enterprises to life. Economic progress may be preceded by waves of creative destruction, as Joseph Schumpeter claimed. But we need to know whether the resources that remain are fertile enough to seed and sustain new growth.

Today digital technologies and borders open to the flow of ideas, goods, and services make it possible to build international partnerships for bringing innovation into production and into the market. For U.S. innovators there are unprecedented new opportunities to draw on production capabilities that they do not have to create themselves. But there are also long-term risks in these relationships, and they go far beyond the loss of any particular proprietary knowledge or trade secret. The danger is that as U.S. companies shift the commercialization of their technologies abroad, their capacity for initiating future rounds of innovation will be progressively enfeebled. That's because much learning takes place as companies move their ideas beyond prototypes and demonstration and through the stages of commercialization. Learning takes place as engineers and technicians on the factory floor come back with their problems to the design engineers and struggle with them to find better resolutions; learning takes place as users come back with problems. And in the challenges of large-scale production, even of humble products like razor blades and diapers, companies like Procter & Gamble find a terrain for innovation that allows them to reap higher profits.

Looking even further down the food chain beneath the companies to the laboratories that generate innovations in the first place, looking at the university laboratories that are the terrain we know best, we saw reasons to fear that the loss of companies that can make things will end up in the loss of research that can invent them. None of PIE experiences in the field were more powerful in concretizing that fear than the visit we made to one of our own colleagues' laboratories. When we went to the basement laboratory in MIT Building 35 of Professor Tonio Buonassisi, a leading researcher on solar cells, he walked us around the lab pointing out all the leading-edge equipment that came from tool makers located within a few hours of Cambridge, Massachusetts. Much of the machinery had been made in close collaboration between the lab and the instrument companies as they handed ideas and components and prototypes back and forth. Used for the first time in the lab, these tools were now being marketed to commercial solar companies. Buonassisi was worried. The news on the U.S. solar industry was looking worse and worse as the economy stalled, as stimulus spending on renewable energy ended, and Chinese competitors hung in, despite losses and low margins. It looked bad for the local companies Buonassisi worked with. And as Buonassisi thought about it, he saw that the collapse of his equipment suppliers would mean real trouble for his research, for he relied on working with them to make new tools faster for more efficient and cheaper cells. Even in a fragmented global economy with instant connection over the Internet to anywhere in the world, the ties that connect research in its earliest stages to production in its final phases remain vital.

On these and many other issues associated with production, we now have the benefit of major new research. The MIT Production in the Innovation Economy (PIE) team has learned much from this recent work, and we owe a special debt to a few contributions in particular that have had great impact on our own understanding: the research of Susan Helper, Susan Houseman, and Erica Fuchs; the reports of the Information Technology and Innovation Foundation (ITIF) and in particular, "*Worse Than the Great Depression: What Experts Are Missing About American Manufacturing Decline*;" Gary P. Pisano and Willy C. Shih's *Producing Prosperity* (2012); the McKinsey Global Institute *Manufacturing the Future: The Next Era of Global Growth and Innovation* (2012); the American Manufacturing Partnership Steering Committee Report on *Capturing Domestic Competitive Advantage in Advanced Manufacturing,* and most recently, the research of the National Academy of Science on innovation policies.[4] Many concerns about manufacturing have been identified and analyzed in this outpouring of work over the past four years. The policy recommendations that have grown out of this body of research are critical contributions to a new agenda for public action.

4 Dertouzos et al., *Made in America: Regaining the Productive Edge.*

Susan Helper, Timothy Krueger, and Howard Wial, "Locating American Manufacturing: Trends in the Geography of Production," (Washington D.C.: Brookings Institution, 2012).

Susan Houseman et al., "Offshoring and the State of American Manufacturing," (Kalamazoo, Michigan: W.E. Upjohn Institute, 2010).

Erica Fuchs and Randolph Kirchain, "Design for Location? The Impact of Manufacturing Offshore on Technology Competitiveness in the Optoelectronics Industry," *Management Science* 56, no. 12 (2010);

Charles W. Wessner and Alan W. Wolff, Editors, "Rising to the Challenge: US Innovation Policy for the Global Economy," (Washington DC: National Academies Press, 2012); ibid.

The MIT Production in the Innovation Economy Study: Objectives and Methods

The approach of the MIT Production in the Innovation Economy project was, however, different from the start. We focused on only one broad question: how production capabilities here and abroad contribute to sustaining innovation and realizing its benefits within our own society. Though some members of the PIE team believe that maintaining manufacturing in the United States is valuable in and of itself, for the jobs it creates, and for national security, the PIE researchers as a group are ecumenical on this point. Our starting point of agreement, rather, is that innovation is critical for a vibrant and productive society. We have organized our research to discover what it takes to sustain innovation over time and what it takes to bring innovation into the economy. We have approached these questions from multiple angles, looking at innovation in products, in processes, in combinations of products and services; at innovation in startups, in large multinationals, in Main Street small- and medium-sized manufacturers, in European and Asian partners and competitors, in hotspots for new technologies, like the biotech cluster of Cambridge Massachusetts, in traditional manufacturing country, like Ohio, and in new manufacturing areas in the Southwest, in Arizona, in China and Germany. We started by asking: what kinds of manufacturing do we need located here in the United States—if any—to support an innovative economy? We tried in each of our research sites within the United States and abroad to trace out the concrete linkages between innovation and manufacturing and to analyze the opportunities and dangers for American prosperity in the changes that have taken place in those linkages.

Because our main focus was on the pathways through which an invention or a new idea about a product or a way of improving a product or process get made into goods and services for sale in the market, we carried out much of our research in firm-level interviews. National Science Foundation statistics state that in 2006-8, 22 percent of all U.S. manufacturing firms reported "a new or significantly improved product, service or process" [5] but as we started our research, we really did not know what they were doing or how they were doing it. We had data, too, on the high-risk venture and corporate funding of startups, but no systematic account of how these firms were finding (or not finding) the full range of inputs they would need on the road to commercializing their innovations. With the interviews and analyses we have now carried out, we believe we have a clearer picture of what takes place within the black box of American manufacturing innovation and commercialization.

In the interviews with senior managers we could trace out in concrete detail the trajectories along which each company moved as it attempted to make its ideas into profits. Where did the

5 National Science Board, "Science and Engineering Indicators 2012."

company get the inputs it needed to bring innovation into production? Did it find these inputs at home or abroad? Where and why did it decide to locate each of its operations? Which parts of its production activities does it believe it needs to keep in close proximity to its R&D in order to bring a product to market and to maximize the gains from its own innovation? In the case of innovations growing out of existing process or product technologies, our interviews in companies allowed us to track interactions between the innovators and the manufacturers in great detail from the point at which the new idea came into play through production into the hands of customers.

Even in the case of big disruptive innovation, there is much we can learn from ongoing relationships in which the seeds of transformation are germinating. We often imagine radically disruptive technologies as if they were comets streaking out of nowhere across the sky of established companies and landing whole new industries in place as old ones disappear. And some new industries, like Facebook, do seem to come out of nowhere. But even for most revolutionary technologies, whether in electronics or materials or information or medicine, the projects are long in the making. It took DuPont ten years to develop Wallace Carothers' lab discoveries in polymers in 1930 into full-scale nylon production—first for nylon stockings in 1940. DuPont's Kevlar took even longer to develop as a commercial product. Today, as we observe discoveries—in biotech, for example—moving along equally lengthy trajectories towards drugs on the market, we have the chance to learn whether in-house manufacturing or manufacturing at a nearby contractor or manufacturing anywhere in the world does better or worse in accelerating the passage from lab to customer; whether ownership of manufacturing alters the distribution of benefits; and who learns what in the process and is in the best position to apply it to bringing the next discovery to life in the world.

In all PIE interviews (see Table 1) teams of MIT researchers raised basically the same questions, with wording adapted to the context and circumstances of each company. The interview template prompted each researcher to ask: *Tell us about 2 or 3 new ideas—new products, new processes, improvements on old products or processes—that you tried to bring to market over the past 5 years. What did you do to try to move it from the stage of being an idea (in a lab, in an R&D center, on the shop floor, in your head) into a product that was sold in the market? Where did you find the capital for the various stages of scale-up? Did you self-finance? Or get venture capital? Or bank loans? Or corporate partners? Where did you find engineers and workers with the right skills? Where did you find technical know-how? Where did you find suppliers? How did you decide what to do in-house and what to outsource? How did you decide where to locate production? What failed and why? What policies make a difference for a company like yours?*

Table 1 : PIE Interviews

China	36
France	2
Germany	32
Israel	1
Sweden	2
Switzerland	3
United Kingdom	2
United States	178
Total	**255**

United States →

Arizona (11)	*Michigan (1)*
California (16)	*New Jersey (3)*
Connecticut (2)	*New York (12)*
DC (2)	*North Carolina (14)*
Delaware (1)	*Ohio (37)*
Georgia (12)	*Oregon (1)*
Illinois (2)	*Pennsylvania (9)*
Iowa (1)	*South Carolina (2)*
Kentucky (1)	*Washington (1)*
Maryland (2)	*Wisconsin (1)*
Massachusetts (46)	

Research on Large U.S. Corporations

The first group in our interview population were American-based multinationals that figure among the largest global investors in R&D.[6] We selected 30 with significant manufacturing operations.[7] Ten of the firms in our sample rank in the top 100 of the Fortune 500 companies. Over the past thirty years these companies have changed from almost entirely U.S. based operations to organizations carrying out R&D and production around the world. From their senior managers we sought to understand strategies for locating innovation, prototyping, pilot production, test and demonstration, early-stage manufacturing and full-scale commercialization in the United States and abroad. In each company, we zeroed in on a few new product lines, and we probed the advantages and disadvantages of U.S. locations for carrying out each of these phases of moving innovation to market.

6 Booz & Company, "The Global Innovation 1000: How the Top Innovators Keep Winning," *Strategy +Business*, no. 61 (Winter 2010). Interview with Senior Vice President Barry Jaruzelski, May 25, 2011.

7 Selection was based on a cross-section of industries and on our possibilities of gaining access.

Research on Start-ups to Full-Scale Commercialization

A second research focus was the population of new companies that grew out of patents that had been created in MIT laboratories and licensed by the MIT Technology Licensing Office over the years 1997-2008. There were 189 of them. The researchers set aside the pure software start ups and zeroed in on companies that were engaged in some form of production, leaving 150 firms.[8] These are starts-ups that are especially well-positioned to succeed, because they

Table 2: MIT TLO Companies, 1997–2008

Industry	# of Firms Started	% of Total	% Receiving Venture Capital*	% Operating^	% Closed	% Merged
Advanced Materials and Energy	15	10	33	73	27	0
Biopharma	58	39	59	55	26	19
Medical Devices	31	21	52	65	3	32
Robotics	5	3	0	60	20	20
Semiconductors and electronics	26	17	85	62	19	19
Other	15	10	33	47	27	27
All Production	**150**	**100**	**55**	**59**	**20**	**21**

* Reported by VentureXpert ^As of June 2012

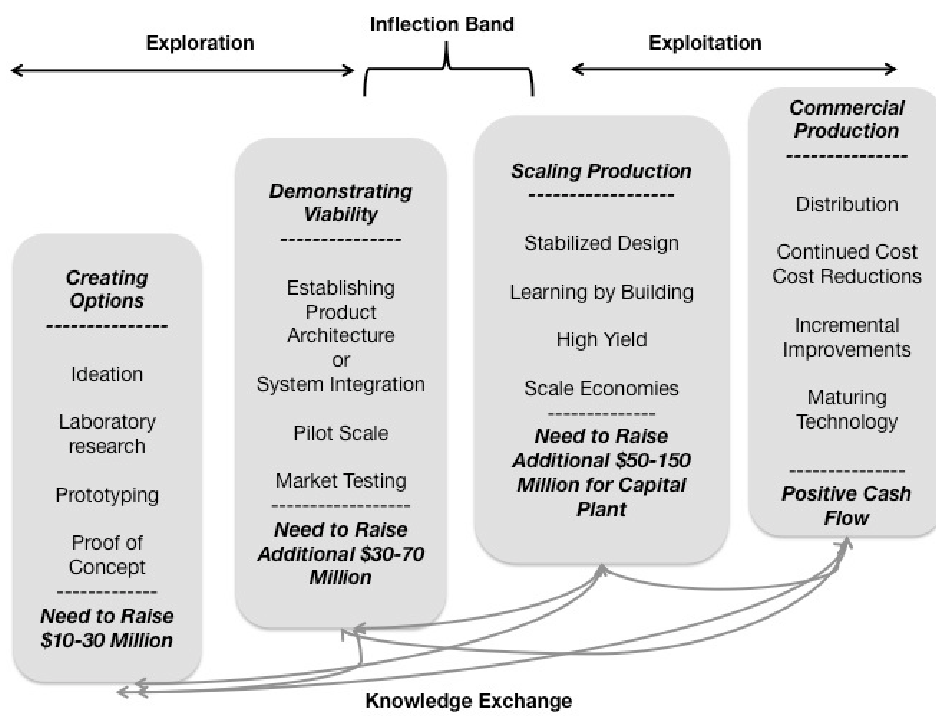
emerge from very strong research labs, because they take their first steps in the world in an extremely dynamic regional hub of innovation with many complementary resources in close proximity, and because they have far better access to early-stage high risk capital than do firms in much of the rest of the country. At those points in the scale-up process where these firms, even with all their relative advantages, find serious difficulties in obtaining the inputs they need for getting their products into the hands of customers, we can anticipate that the "average" new American firm based on innovative technologies will also be having trouble, so there are important lessons to be learned from their experience. There are, of course, many

8 There were 29 software firms and an additional 10 firms for which for the researchers could not find any recent records, leaving 150 production-oriented start-ups.

reasons firms might fail to find resources to scale-up, relating to the market, or competitive landscape, or the product, or management. But with the MIT sample we sought to stack the deck in favor of finding winners—and then through analysis of their progress at each stage of development, we tried to locate and analyze their challenges in reaching scale. The research team learned that on the whole these highly innovative companies were able to obtain funding through relatively long periods (even up to ten years) of early phases of scaling up through early market demonstration. But many of them when they came to the stage of moving to full-scale commercialization, could not find finance in the U.S. As many of them made the transition from venture funding to high-volume manufacturing, they eventually had to look for foreign investors and often moved abroad to manufacture their products.

Figure 1: Scaling up

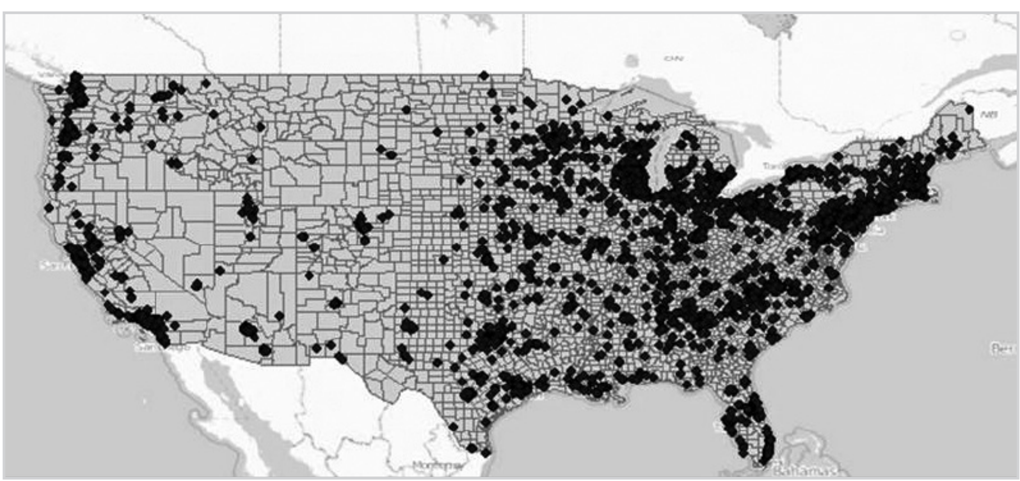
Adapted from Figure 2.1, "The four stages of energy innovation," page 11, in Richard K. Lester and David M. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost, Low-Carbon Energy System* (Cambridge, Massachusetts; London, England: The MIT Press, 2011).



Research on "Main Street Manufacturers"

The third target population within the PIE company sample were small- and mid-sized U.S. manufacturers. To figure out how to raise the water-level of all kinds of innovations—product, process, service, incremental, radical, repurposing, business model—flowing into the economy, we knew we needed to look beyond Silicon Valley and Cambridge Massachusetts. PIE researchers obtained a list of all U.S. manufacturing firms which had doubled their revenues and increased their headcount between 2004 and 2008.[9] Of these we retained the 3,596 manufacturing companies in the U.S. which had more than $5 million in annual revenues and more than 20 employees. These companies seem to be, at a minimum, *viable* companies, hence ones in shape to potentially carry forward new products into the market. In Arizona, Georgia, Massachusetts, and Ohio we carried out interviews with 53 of these firms. To this group we added 43 similar firms that we discovered through other branches of our work. In each of these companies, PIE researchers asked the same questions about new products and processes and the inputs to bring them to market.

Figure 2: Company locations of the 3,596 High-Impact Companies with more than $5 million in annual revenues and more than 20 employees



9 The data was acquired from the Corporate Research Board, LLC and is described in Spencer L. Tracy, Jr. "Accelerating Job Creation: The Promise of High-Impact Companies," Corporate Research Board, LLC for SBA Contract Number SBAHQ-10-M—144. www/sba.gov/sites/default/files/HighImpactReport.pdf.

Innovation is not all about patents. Only rarely do the novel activities of established small- and medium-sized manufacturers correspond to the OECD's Frascati Manual and "Oslo" definitions of "research and development" as "creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications."[10] But there's also a hidden wealth of innovation in process, business organization, and manufacturing across America in firms of all sizes. In the Main Street manufacturers sample, we discovered a few firms with leading-edge innovations (and patents). But for most of them, their major innovative contribution is repurposing technologies developed in one sector for altogether different uses. A third-generation CEO of a Midwest company that makes steel components, for example, told us of developing special lighter steel he had used in construction and experimenting with bringing it into new work he was doing in defense contracting. If his ideas work out, it would help reduce the weight of aircraft carriers and lower their energy consumption. For yet another important group of Main Street manufacturers, their role in innovation is as suppliers providing vital components and services to enable scale-up in other companies. One such company, Mass Tank in Middleboro, Massachusetts, exemplifies the pattern. It's a fifty-employee firm that does its main business in fabricating tanks and selling tank inspection services for chemical, food, pharmaceutical, and water industries. But it is also working with five start-ups in the region and going back and forth with their engineers developing new materials and components that may someday be part of a blockbuster new product that Mass Tank will have helped these innovators to bring to market. In these suppliers, the greatest strength is a combination of design and fabrication capabilities. Andy Yahraus, CEO of Modern Industries, an Arizona supplier that works for aerospace, defense and for semiconductor industries, told us:

> Once components are decoupled from design, there's a reduction in the latent knowledge of how things are made. The process has to be simplified when things are "leaned out." So, when there is a game-changing design, there is no latent base that allows 3rd world manufacturers to make it. Those of us American/European companies that stay competitive are then in great demand. The expectation is that we'll contribute to design in manufacturing. The OEM may give us a terrible drawing—so you have to fix it. OEMs have few people who can read blueprints. Sometimes they give us blueprints, sometimes they just give us a solid model and we detail it out. We then pass drawings back and forth. There's a shortage today of people who understand what every component needs; and without engineering experience in a factory, you can't learn how to do the interpretation necessary to making a drawing into a product.

10 OECD, "Proposed Standard Practice for Surveys of Research and Experimental Development—Frascati Manual," (Paris: OECD, 2002).

But in this company as in most of the others in this category that we interviewed in the U.S. all growth depended on their internal resources. They were not finding any complementary capabilities they could draw on in the industrial ecosystem as they tried to develop new components: no outside funding, no connections with community colleges, no trade associations, no research consortia (all regular fixtures, we would discover, on the landscape of German companies in the same industrial sector.) As we wondered why the contributions to innovation of the Main Street manufacturers did not lead to greater profits and faster growth, the comparison with Germany was inevitable. An Ohio machine toolmaker is not going to take off like Microsoft or Facebook, but we saw underexploited possibilities. How could we galvanize more innovative activity within Main Street manufacturers, a faster uptake of new technology, and a tighter enabling connection with new start-ups across the economy?

Lessons from Abroad: Germany and China, Scale-Up Economies

The fourth group of firms in the PIE sample were foreign: mainly German (32) and Chinese (36) companies. In most respects, Germany and China could hardly be more different from each other. Germany is one of the world's richest and most advanced industrial societies. China, for all of its remarkable progress, is still a poor-to-middle income country with rather low productivity and few companies that compete in world markets on the basis of unique products or processes. Yet both of these countries have companies that are world-beaters in scaling up innovation to market. In both Germany and China we found compelling examples of innovative manufacturing and scale-up that challenged many of our ideas about why innovative companies in the U.S. so often falter before attaining the size and capacity to reach large numbers of customers. In interviews with senior managers in the two countries, as in our interviews in the United States, we tried to track how a company advanced new ideas from the earliest stages of development through to prototyping, test and demonstration, pilot production, and large-scale commercialization.

Innovation in Germany builds on legacies: in industrial specializations, longstanding relationships with customers, workforce skills, and proximity to suppliers with diverse capabilities.[11] The potential of German patterns extends well beyond defending niches against low-cost competition with incremental advances. They create new businesses, not usually through start-ups—the U.S. model—but through the transformation of old capabilities and their reapplication, repurposing, and commercialization. The companies we interviewed had moved from autos to solar modules, from semi-conductors to solar cells, from machine tools to make spark plugs to machines to make medical devices like artificial knees. In the Main Street manufacturers we interviewed in the U.S. they usually had only their own material,

11 For the reuse of legacy capabilities in industrial change, see Suzanne Berger and MIT Industrial Performance Center, *How We Compete: What Companies around the World Are Doing to Make It in Today's Global Economy* (New York: Currency Doubleday, 2005).

human, and financial resources to draw on when they tried to scale-up an innovation. The Germans had not only their own legacy resources, but also access to a rich and diverse set of complementary capabilities in the industrial ecosystem: suppliers, trade associations, industrial collective research consortia, industrial research centers, Fraunhofer Institutes, university-industry collaboratives, technical advisory committees. A survey of 744 industrial collective research projects undertaken in Germany 2003-5 found 293 different organizations involved in just those programs.[12] It's impossible to understand the different fates of manufacturing in the U.S. and Germany without comparing the density and richness of the resources available in the industrial ecosystem across much of Germany to the thin and shrinking resources available to U.S. manufacturers across much of our country.

The China interviews showed firms emerging with remarkable innovative capabilities in manufacturing. China's great initial assets were cheap factor prices—cheap land, labor, capital and an undervalued currency. Low-cost labor allowed Chinese companies in apparel and footwear to make huge inroads in Western markets. But today the PIE research team found Chinese firms in emerging industries like renewable energy. These are firms that excel in scale-up to mass manufacturing not because of low-cost labor, but because of their ability to move complex advanced product designs into production and commercialization. The huge China market is of course a major draw for investors of all nationalities. But even in those industries in which the main customer markets are still in the West, as for consumer electronics, photovoltaic cell and module production, American and European innovators are turning to Chinese partners. Increasingly the reason is the specific capabilities in knowledge-intensive scale-up they find in China. These capabilities involve: reverse engineering and re-engineering a mature product to make it more rapidly and efficiently; making designs into new-to-the-world products and processes; and indigenous product innovation. In each of these categories PIE researchers interviewed Western companies and their Chinese partners and walked through the Chinese plants with engineers to track how exactly innovation was being produced.

Research on Jobs and Skills

Two other research groups formed within PIE to analyze two critical inputs to bringing innovation to market: jobs and skills and advanced manufacturing technologies. For these research modules, the project used surveys as well as interviews. The group working on jobs and skills talked with companies, community colleges, high schools, and labor market programs across the country. Their sample of close to 1000 manufacturing establishments is the first nationally representative data on what skills are needed and shortages occur. Since production workers account for over 40 percent of all those employed in manufacturing, the team focused on whether there is a shortage of skills in this population, as many have claimed. What skills do your workers need? employers were asked. Basic reading, writing and math? To use a computer?

12 Michael Rothgang, Matthias Peistrup, and Bernhard Lageman, "Industrial Collective Research Networks in Germany: Structure, Firm Involvement and Use of Results," *Industry and Innovation* 18, no. 4 (2011). p. 395.

To work in teams? To take independent initiatives? Have skill requirements increased significantly over the past five years? (Only 7 percent of the respondents thought so.) How long does it take to identify and hire the right candidate? The median answer was four weeks. Just under 20 percent of the establishments had some long-term vacancies (over three months) equal to 5 percent or more of their core production workers. The analysis drilled down into the job categories and firm types where there do seem to be problems finding candidates with the right skills. The problems centered in jobs requiring skills not generally available in the region; jobs requiring advanced math skills; and very small companies. Further probing showed that firms with few or no connections to other companies in their area and few or no connections to local schools also had more hiring issues. The research group conducted interviews in regions with programs that have brought together industry, schools, and government funding to work on these problems with some success.

Research on Advanced Manufacturing Technologies

The team working on advanced manufacturing technologies queried engineering colleagues across the country in order to try to locate the potential sweet spots for technologies that could radically speed up the passage of new goods and services from the lab bench to market. Using the surveys and interviews, the team identified and ranked the promise of seven major technology groups. They are important because they could accelerate growth and energy efficiency by transforming manufacturing. Today, manufacturing is a lengthy and often inefficient process in which the raw materials which nature provides are pushed through stages of fabrication, assembly, and warehousing and emerge as goods for sale in the market. In a future which new technologies could enable, manufacturing might become a rapid process in which human-designed and engineered materials would be pulled by demand through continuous manufacturing and customization to meet specific and differentiated human needs. Today manufacturing remains highly centralized and concentrated in large factories and components and finished goods are transported at great cost and with high impact on the environment through long supply chains. Trends to offshoring and outsourcing have made manufacturing plants bigger and the distances goods traverse even longer. Tomorrow we can imagine technologies that would "destroy the tyranny of bulk" and distribute manufacturing, thus making it possible to manage capacity and demand flexibly through networks of small, localized manufacturers linked by Internet.

The Great Transformation: The New Corporate Structures of the American Economy and the Origins of the Production Problem

As we started to analyze the data from the interviews and the surveys and began to discover the stages at which promising innovations were stalling or moving abroad before reaching commercial scale in the U.S., we stood back to consider how the U.S. economy had reached a point where scaling up its own best ideas had become so problematic.

Fifty years ago, at the high water mark of American economic dominance in the world, 29 percent of U.S. workers were employed in manufacturing (January 1960), wages of the manufacturing workforce had been rising for decades, and innovation and manufacturing moved together in lockstep to produce a vast new stream of products for the market. Invented in the USA meant made in the USA. As described by theorists of the "product cycle," new products were first scaled-up, standardized, mass produced, and brought to high levels of performance and reliability in the advanced industrial countries in which they were invented.[13] Only after the production of the good had been thoroughly mastered and standardized and after the initial premium of first mover advantages had been exhausted—when production matured and the good became a commodity—did manufacturing shift to less-developed countries with less-skilled workers.

Today we stand at a different point in history. Huge trade deficits are there to remind us that invented in the USA no longer means made in the USA. Even the first generations of iPhones and iPads were not first made in the U.S. and then transferred to Asia. Given the density, synergies, and capabilities that now reside in Asian supply geographies, it is most likely that the next generations of consumer electronic products designed in the U.S. will still be made in Asia—even if wages continue to rise there. Research on the products and processes in emerging high tech sectors like solar and wind energy and batteries shows that very early phases of scaling up of these new products are taking place outside the U.S. In some of these industries today, it would be very difficult to do early-stage manufacturing in the U.S., because the technical expertise, the workplace skills, equipment, and the most advanced plant lay-outs are no longer present in the country or have degraded and fallen behind state-of-the-art elsewhere.

13 Raymond Vernon, "International Investment and International Trade in the Product Cycle," *Quarterly Journal of Economics* 80(1966).

The opening of the world economy and the rise of strong new manufacturing capabilities across the globe make it possible to find and to use production located outside our national borders. It's not only in "mature" industries like apparel that manufacturing has moved overseas. It's in newer sectors, like solar cells, wind turbines, and batteries. In the past chip design and chip fabrication had to be carried out within the four walls of the same company; today chip designers can send files of digital specifications to semiconductor fabrication plants anywhere in the world for production. Apple can define, design, and distribute iPods and iPhone and iPads in the U.S. without having any significant production facilities here at all.[14]

The possibilities for innovators and designers to draw on the manufacturing capabilities of the entire world has stimulated a huge wave of new enterprise creation both in the U.S. and in the developing economies. On the face of it, this is an enormously positive outcome. What we do not know, though, across different industries—and particularly for emerging new high-tech domains—is whether the separation of innovation from manufacturing will allow innovation to continue full-bore at its original home, or whether separation comes at the price of learning and creation of capabilities that might produce future innovation at the original home base. Separating innovation and manufacturing—in different companies, or in different locations—might make it unlikely that a firm would gain full advantage from implementing technological advances *within* manufacturing, for example, from learning how to accelerate the scale-up of a biotech drug from test tube to mass production or learning how to fabricate semiconductor chips at lower volume, higher value, and lower cost to run the medical devices that aging generations of baby boomers will need to keep them healthy and functioning at home and out of hospitals.

How did this new global economy of fragmented research, development, production, and distribution come into being? What does it mean for the future of the U.S. economy? The causes of this transformation are important to grasp, because they had their origin in changes in U.S. financial and industrial structures whose full consequences we are only now beginning to be able to weigh. What stands out in our analysis as we have tried to reconstruct what happened to manufacturing in the United States is the tectonic shift in corporate ownership and control that took place well before globalization or Asian development had come into full play.

From the 1980s the large vertically-integrated corporations that had long dominated American manufacturing began to shed many of their business functions from R&D and

14 Because of Apple's spectacular success, we frequently refer to this model in our work. Apple did not agree to be interviewed for this project, and we have had no access to Apple other than to publicly-available information about the company.

design through detailed design to manufacturing and after-sales services.[15] These activities had all once been joined under one corporate roof. Indeed most management mantras of the time proclaimed that the tighter the integration of functions, the better the company performed. By 2013, however, very few large American companies remain with vertically-integrated structures. Companies like General Electric or Procter & Gamble with a wide range of different businesses under one corporate roof and a predominant preference for integrating research through production are the exception. The great new American companies of the past 30 years like Dell, Cisco, Apple, and Qualcomm have little or no manufacturing in-house. Perhaps the single most compelling factor in the 1980s that led to shrinking the perimeter of the corporation and reorganizing it around "core competence" came from financial markets: higher stock market valuations of leaner, "asset-light" companies which had weeded out their less-profitable divisions and reduced their diversification.[16] First among the business functions that companies started moving out of their own corporate walls was manufacturing—for that produced reductions in headcount and in capital costs that stock markets immediately rewarded. Advances in digitization and modularity in the 1990s made it possible to carry out this strategy and to outsource production to manufacturing subcontractors like Flextronics and Jabil and eventually to foreign suppliers and contractors like Taiwan Semiconductor Manufacturing Company, Quanta, and Foxconn.

Today, of course, a more complete picture of the transformation of the global industrial landscape of the past thirty years would also have to include many developments that took place outside the United States. Many of them are of fairly recent origin: the radical dismantling of border-level barriers to capital and trade flows and China's entry into WTO in 2001; the development of Hong Kong and Taiwanese-led supply chains of agile, dynamic subcontractors in Asia with access to huge reservoirs of cheap semi-skilled and skilled labor; new digital technologies that enabled the fragmentation of value chains; the emergence of great new Asian consumer markets requiring localization of production. All of these factors would have enormous importance for the restructuring of the world economy.

But the starting point for the analysis we have conducted of U.S. capabilities needs to be pushed back to the 1980s and to the transformation of the structures of the vertically-integrated firms. Out of those changes in corporate structure have come not only great new opportunities, but also some of the most difficult hurdles we face today in trying to move U.S. innovation into the market. Here we can only list some of these challenges:

15 See a fuller account of these changes in Berger and MIT Industrial Performance Center, *How We Compete: What Companies around the World Are Doing to Make It in Today's Global Economy*; ibid.

16 Gerald F. Davis, *Managed by the Markets: How Finance Re-Shaped America* (Oxford: Oxford University Press, 2009).

- Vertically-integrated enterprises used to organize and pay for educating and upgrading the skills of much of the manufacturing workforce. They had the resources to do this. And long job tenure meant companies could hope to recoup their investment over the course of the employees' careers. Many of the employees who were trained in big companies or in vocational schools they supported ended up working for smaller manufacturers and suppliers. Today, American manufacturing firms are on average smaller, and have fewer resources. They do not plan to hold on to their employees for life. They cannot afford to, or, in any event, do not, train. How do we educate the workforce we need?

- Vertically-integrated enterprises like AT&T used to support long-term basic research in centers like Bell Labs and Xerox PARC and Alcoa Research Lab, each employing thousands of scientists and engineers. As corporate structures have been resized, basic research has been drastically cut, these centers have mostly disappeared, and corporate R&D is now far more tightly linked to the near-term needs of the business units. How should we fund a strong stream of basic and pre-competitive research today? If much cutting-edge research no longer is taking place within companies—but in universities or small start-ups or in government labs—how to propel these innovations through to commercialization? How to diffuse new technologies into established companies?

- When innovation grew out of large firms, they had the resources to scale-up to mass commercialization. In the thirties, a corporation like DuPont not only invested for a decade in the fundamental research that led to nylon, but once the lab had a promising product, DuPont had the capital and the plants to bring it into production. Today, when innovation is more likely to emerge in small spin-offs or out of university or government labs, where do the scale-up resources come from? How available is the funding needed at each of the critical stages of scale-up: prototyping, pilot production, demonstration and test, early-manufacturing, full-scale commercialization? When scale-up is funded mainly through merger and acquisition of the adolescent start-ups and when the acquiring firms are foreign, how does the American economy benefit?

- Big American corporations used in effect to provide public goods through spillovers of research, training, diffusion of new technology to suppliers, and pressure on state and local governments to improve infrastructure. These spillovers constituted "complementary capabilities" that many others in the region could draw on, even if they had not contributed to creating them. As the sources of these "complementary capabilities" have dried up, large holes in the industrial ecosystem have appeared. How can these capabilities be recreated and sustained in order to maintain a terrain favorable for innovation?

As the PIE researchers looked across the interviews and surveys we carried out in the project, we saw the holes in the industrial ecosystem as the single most challenging obstacle to creating and sustaining production capabilities in the United States that enable innovation to come to market. What we have come to think of as "holes" might be less picturesquely described as "market failures" or as absence of "complementary capabilities" that companies can draw on to supplement their own resources when they seek to develop their new ideas. These holes in the industrial ecosystem are ones that have been hollowed out by the disappearance of large numbers of suppliers under pressure from global competition and by the disappearance of local capabilities once provided by large corporations as part of their own business operations. As national banks have bought up local banks, local bankers with intimate understanding of local manufacturing have become an endangered species—making it harder to get bank loans. Critical suppliers have dwindled in numbers. In small firms as well as large defense contractors, we found companies considering the costly option of internalizing some of the functions their suppliers currently perform, for fear that what's become a single-source supplier will go out of business. These are concerns even for current production. But the difficulties are far more challenging when a company seeks to develop a new or improved product or process. New inputs are needed, like different skills, finance, and components that firms cannot efficiently produce all by themselves. Even startup companies with great novel technologies and generous venture backing cannot do it all in-house: they need to find suppliers, qualified production workers and engineers, expertise beyond their own. Established Main Street manufacturers in the regions we visited find little beyond their own internal resources to draw on when they seek to develop new projects. They're "home alone." This environment is far different from that of the German manufacturers we interviewed who are embedded in dense networks of trade associations, suppliers, technical schools, and applied research centers all within easy reach.

Pathways for Growth

There is much work to be done on all fronts to renew the production capabilities that the United States needs in order to gain full value from its innovation. The AMP Steering Committee Report *Capturing Domestic Competitive Advantage in Advanced Manufacturing (2012)* to the President's Council of Advisors on Science and Technology, has laid out a very broad agenda for action that addresses many of the issues that the PIE research modules have identified. The PIE taskforce, however, believes that one objective is most urgent: rebuilding the industrial ecosystem with new capabilities that many firms of all kinds could draw on when they try to build their new ideas into products on the market. Many states and localities have invested in programs to create "clusters" in emerging industries: firms specializing in biotech, or medical devices, for example. These efforts at building clusters have worked in a few places, but failed in many. We have much less experience with trying to generate common resources for an industrial environment with many diverse firms in diverse sectors. Yet new research suggests that it's the co-located interdependencies among complementary activities , not narrowly specialized clusters, that produce higher rates of growth and job creation, and they do so across a broad range of industries, not just in high-tech or advanced manufacturing. [17] The examples we have observed in the PIE research with trying to create public goods—or semi-public, or club goods—in the industrial ecosystem is an approach that may pay the greatest dividends.

The cases we have studied in some detail are extremely diverse, but the institutions they have set in place involve a few common principles. The key functions that such mechanisms perform are convening, coordination, risk-pooling and risk-reduction, and bridging. They are public goods that the market does not generate.

There are initiatives in which a private company or a public institution performs a *convening function*. The initiative usually starts with the "convenor" putting new resources on the table for use by others on condition that they too contribute to the pot. One example came from our Ohio interviews: the Timken Company, a manufacturer of tapered bearings and of specialty steels, initiated a partnership with the University of Akron and transferred Timken's coatings laboratory, its equipment, and several of its key researchers to the university. With resources from the company, the university, and the state, new graduate degree programs are starting; a new consortium on coatings and engineered surfaces has been created that is open to other corporate members; and a set of promising coatings technologies that had been "stranded" in a bearings company can now be developed as potential start ups in which both the university and the corporate consortium members can invest. Potentially, companies from outside the region might join, but much of the value from participation will derive from face-to-face presence in the labs at the University of Akron, from being able to use university labs (funded in part at least with public money) instead of keeping these facilities in-house, and from the chance for local companies to hire graduates. Another example is the State of New York's investments in facilities for semiconductor manufacturing that bring together private companies, research laboratories and degree programs at the state university, and SEMATECH, an industrial consortium of leading semiconductor and semiconductor equipment manufacturers. Here the convenors hold out the lure not only of the use of common facilities and expensive equipment and training and proximity to cutting edge researchers, but also of participation in roadmapping new technologies, which lowers costs and risks for all the industry partners. In contrast to tax breaks, which many states hand out, new resources in these cases are embedded in institutions which do not stand or fall on the participation of any one member. "Convening" brings into existence new collaborations and new common resources.

In the cases we have studied, sometimes the lead in creating new *coordination* was taken by a private company. In other cases we examined, coordination came from a public intermediary. In Springfield, Massachusetts, the Hampden County Regional Employment

17 Mercedes Delgado, Michael E. Porter, and Scott Stern, "Clusters, Convergence, and Economic Performance," (National Bureau of Economic Research, 2012). Working Paper 18250.

Board (REB) is mandated by federal job training legislation to work with firms, localities, and educational institutions in the operation of the Workforce Investment Act. When the local machining association faced a shortage of skilled workers as the result of the closing of several large companies that had previously trained apprentices, it approached the REB. The REB brought the firms together with five vocational high schools and two community colleges. The connections between the schools and the companies had been thin and intermittent. With active intervention from the REB, the parties started to work on curriculum development; on training programs for supervisors and for unemployed workers; organized career fairs and firm visits to encourage high school students to consider machining jobs; and the gaps began to close.

Risk-reduction and risk-pooling are among the original functions for all forms of insurance and standard setting, and virtually all trade associations develop these functions to a greater or lesser extent for their members. For example, as we traced out the network mentioned above that connects Mass Tank to start up companies in the New England region, we discovered Mass Tank itself depends on a trade association, the Steel Tank Institute, for standards, testing, expertise, and insurance. The dangers of leaky tanks create enormous potential hazards—and lawsuits—and no small company on its own could afford adequate insurance from the regular insurance market. By working with the Environmental Protection Agency to develop safety standards, the Steel Tank Institute has been able to offer its members technology, testing, and insurance that covers them.

These very old uses of association for risk-pooling today are being put to new purposes in harnessing them to innovation and to commercializing innovation in the United States.. The first of the National Manufacturing Innovation Institutes, the National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio offers companies, universities, and government agencies a way to distribute the risks of investing in new technologies while still deriving many of the potential benefits. As one industrial partner from a metal-working company expressed his perception of the risks: "We don't make plastic toys, so we couldn't justify investing in-house in a technology like this that may just be a flash in the pan. But just suppose it does work out and we're not close enough to it to have a voice in shaping its development...what then?" For those firms that do already have proprietary stakes in additive manufacturing there are yet other risks, and some forms of association with NAMII can help protect against them. For a region like Northeast Ohio and Southwest Pennsylvania, there's the enormous promise of technologies that could revitalize many of the small and medium-sized manufacturers but no way of finding a single industrial champion that would have an interest in carrying the project. The gains from 3-D printing if it ever succeeds in overcoming its many current limitations would be harvested by a multiplicity of users across very diverse industrial sectors. When gains from innovation are significant but distributed thinly across many firms, it's unlikely that any single one of them will invest enough to bring it to life. NAMII offers the potential of a way of inducing collaboration and a way of spreading its risks that could bring a new technology to life and inject new vitality into the regional economy.

The cases we have described as exemplifying new approaches to rebuilding the industrial landscape are so new that we cannot know if any one of them will ultimately work or not. If we believe, nonetheless, that they have a real chance, it's because what's held manufacturing in the United States in the last resort—even as so much turned against it—was the advantage firms gain from proximity to innovation and proximity to users. Even in a world linked by big data and instant messaging, the gains from co-location have not disappeared. If we can learn from these ongoing experiments in linking innovation to production, new streams of growth can flow out of industrial America.

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